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SELECTED TOPICS IN NUCLEAR GEOPHYSICS

Mihai BORSARU

Commonwealth Scientific and Industrial Research Organization
CSIRO , P. O. Box 883, Kenmore, Qld 4069, Australia
E-mail: mihai.borsaru@csiro.au

Nuclear Geophysics is essential to the oil, gas and uranium industries. The initial development of nuclear geophysics was focused on developing techniques needed by the oil industry. Developments in nuclear physics and computational analysis were immediately used this field. Today, techniques developed in nuclear geophysics are also used by the coal and metalliferous mining industries and contribute to a substantial increase in productivity. This article tries to introduce the reader to the nuclear borehole logging. The applications of natural gamma radiation, backscattered gamma-gamma and prompt gamma neutron activation analysis are reviewed.

1. INTRODUCTION

Nuclear borehole logging is a subset of nuclear geophysics closely following developments made in theoretical and experimental nuclear physics. Borehole geophysical methods have been used extensively for well logging in the exploration for petroleum. The methods are usually applied for in situ measurements of the physical properties of the rock surrounding the hole. Nuclear geophysics is essential for the oil and gas industries where very deep holes are drilled (thousands of meters). Due to the deep penetration of the gamma-radiation and neutrons, nuclear logging can locate the presence of oil or gas behind the well casing. After the initial success in the petroleum industry, nuclear geophysics has become of interest to the mineral, uranium and coal mining industries. The scale of the application of nuclear techniques to geophysics can be compared to the atomic energy industry itself. Today, very sophisticated nuclear methods are used in the petroleum and gas industry. Depths at which prospecting and exploration of oil and gas fields are conducting have become greater. This necessitated the development of new detectors for the detection of gamma radiation. The detectors must withstand high temperatures and mechanical shocks.

The advent of the computer had an enormous contribution to the development of nuclear geophysics. Monte Carlo simulation programs running on laptop computers are routinely used for designing and developing new tools and techniques. Data basis for neutron and gamma ray cross sections measured in nuclear physics laboratories cover a wide range of nuclei and are in the public domain, accessible to physicists that work in nuclear geophysics. Current Monte Carlo simulations are very accurate.

The laboratory analysis of core samples retrieved from boreholes and nuclear logging are complementary. Although the core can provide the full information which can be extracted from a borehole, nuclear logging is capable to provide information almost instantaneously. The volume of rock sampled by nuclear borehole logging is also much larger than the core samples and thus provides better sampling statistics, especially in heterogeneous deposits.

Nuclear borehole logging techniques are either passive (natural gamma) or active. In passive logging, the natural radiation in the borehole is measured by an appropriate detector, while in active logging; an artificial radioactive source will provide the radiation measured by the detector. The radioactive source can

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be either a gamma ray source, as in the gamma-gamma technique, or a neutron source, as in the prompt neutron gamma activation analysis (PGNAA).

This article presents a few aspects of nuclear geophysics with the emphasis on borehole logging geophysics. The structure of the paper is to give a short overview of the most common gamma and neutron sources (section 2) and detectors for detection of gamma radiation (section 3) used in nuclear borehole logging. There are many types of detectors and new types are being developed. The paper describes only the most common detectors used in this field. The fundamentals of natural gamma radiation (section 4), scattering and absorption of gamma radiation (section 5) and scattering and absorption of neutrons (section 6) are presented and a few relevant applications are shown. The article only has the scope to make the reader understand what nuclear geophysics is about. Today nuclear geophysics is a well developed and sophisticated field of geophysics and there are many books published in this field.

2. GAMMA AND NEUTRON RADIATION SOURCES

The most common gamma-ray sources used in nuclear borehole logging are ^{137}Cs, ^{60}Co and ^{133}Ba. ^{137}Cs has a half-life of 30 years and disintegrates by releasing gamma-rays of energy 662 kev. ^{60}Co has a half-life of 5.62 years and disintegrates by emitting gamma-rays of 1.173 and 1.332 MeV. ^{133}Ba has a half-life of 7.2 years. The most important gamma-rays emitted by ^{133}Ba have energies of 32, 80, 302 and 356 keV. The possibility of replacing radioactive gamma-ray sources with accelerator sources has been investigated. The advantage of using accelerator sources is that they can be turned on when they are in the borehole and turned off when they are out of the borehole, thus minimising the radiation exposure to users. Accelerator sources are not commonly used in the coal mining industry.

The neutron sources most commonly used in borehole logging are ^{252}Cf, Am-Be and the neutron generator using the D-T reaction. The most commonly used type today in the coal and mineral industry is the isotopic fission source ^{252}Cf with a mean energy of ~ 1.8 MeV and a peak at ~ 1.1 MeV. Figure 1 shows the neutron energy spectra of ^{252}Cf and the ^{241}Am-Be neutron source based on the α-n reaction. The figure shows that the mean energy of the fission neutron spectrum of ^{252}Cf is lower than that of Am-Be. This makes the ^{252}Cf neutron source more suitable for prompt gamma neutron activation analysis applications. Also, ^{252}Cf is more environmentally acceptable for borehole logging applications because of its shorter half-life (2.64 yr) compared to 456 years of Am-Be. If there were an accident and the source can not be retrieved from the borehole, it is better to loose a source with shorter half-life that will decay in time. However, one disadvantage with using the ^{252}Cf neutron source is that the source must be replaced every 4-5 years due to its fairly quick decay.

The neutron generator is an alternative neutron source. One advantage of using the neutron generator is that it can be turned off when it is outside the borehole and there is no need for heavy shielding to protect the personnel from radiation. Another advantage is that the neutron generator produces high-energy neutrons (14 MeV) which are suitable for methods based on inelastic scattering. By pulsing the neutron generator, it is possible to separate the gamma-ray spectra produced by neutron inelastic scattering from those excited in neutron capture reactions. Although the neutron generator is widely used in oil logging it is not used in the coal mining industry due to its high cost and limited life of the generator tube.

3. RADIATION DETECTORS

The most common detectors for γ-radiation are the high purity solid-state Ge detectors (HPGe) and the scintillators NaI(Tl), CsI(Na) or CsI(Tl), and $Bi_4Ge_3O_{12}$ (commonly referred to as BGO). The NaI(Tl) detector is widely used in industrial applications. It has the best energy resolution among the scintillation detectors, it can be grown to large volumes and it operates at ambient temperatures. CsI(Tl) is also a common scintillator. It has a higher density (4510 kg/m^3) than has NaI(Tl) (3670 kg/m^3) and is therefore more efficient for detecting high energy γ-rays. However, the energy resolution of CsI(Tl) is inferior to NaI(Tl) because CsI(Tl) has a light output of only 83% of that of NaI(Tl). CsI(Tl) is more resistant to to mechanical shock than is NaI(Tl). Both NaI and CsI are hygroscopic. Improvement in photomultipliers and packaging

has increased the quality of the scintillation detectors for withstanding shock and large variations in temperature.

BGO has greater stopping power than both the NaI(Tl) and CsI(Tl) scintillators, especially for high energy γ-rays. The density of the BGO crystal is 7100 kg/m^3 and the effective atomic numbers for BGO, NaI(Tl), CSI(Tl) and HPGe are 70, 48, 54 and 32 respectively. BGO is commonly used in prompt gamma neutron activation analysis applications due to its high efficiency for high energy γ-rays that follow the neutron-capture process and the fact that the crystal is less sensitive to activation and capture reactions than either NaI(Tl) or CsI(Tl). Drawbacks regarding BGO are its low energy resolution (light output is only 8% of that of NaI(Tl)) and gain sensitivity to variation in temperature.

The high resolution HPGe detector is used in neutron capture applications for multi-element analysis. It is not commonly used in borehole logging for coal applications due to its low efficiency for high energy γ-rays. Another disadvantage of using the germanium detector in neutron capture work is its sensitivity to neutron radiation damage. The sensitivity limits both the choice of the neutron source strength and the distance between the neutron source and the germanium detector.

There are other scintillators tested for the detection of γ-radiation showing potential for borehole logging applications. One should have in mind that the development of better detectors for the detection of γ-radiation will have a great impact on this technology. However, the detectors mentioned above are currently the most commonly used ones.

4. PASSIVE LOGGING – NATURAL GAMMA-RAY

All rocks and soils contain a great number of radioactive elements that emit γ-radiation. The three main sources of natural γ-rays are potassium, decay products in the uranium series and decay products in the thorium series.

Of the three naturally occurring isotopes of potassium, only ^{40}K is radioactive; it has a half-life of 1.28 x 10^9 years and isotopic abundance of 0.0118%. ^{40}K decays to ^{40}Ca and emits a γ-ray of energy 1.46 MeV. Because many rock-forming minerals contain potassium, it is the commonest natural γ-ray encountered in nature.

^{238}U and ^{235}U are more abundant among the isotopes of uranium, with ^{238}U making up 99.3% of the total. Each isotope of uranium dacays by α-emission to an isotope of thorium. Thorium and its daughters are also radioactive and a decay chain of the parent isotope is produced. ^{238}U has a half-life much longer than its radioactive decay products, and in an undisturbed medium a secular equilibrium is established. A radioactive decay series is said to be in a state of equilibrium when the number of atoms of each daughter being produced in the series is equal to the number of atoms of that daughter being lost by radioactive decay. ^{214}Bi is one of the isotopes produced in the ^{238}U chain and decays emitting a 1.765 MeV γ-ray. This is a characteristic gamma-ray peak corresponding to uranium contribution in a natural gamma-spectrum.

^{232}Th has a decay chain similar to the decay chains of uranium. One prominent γ-ray of energy 2.6 MeV, emitted by the daughter product ^{208}Tl, is usually used for the determination of thorium concentration. Like uranium, thorium is widely found in rocks. The average thorium content of the continental upper crust is 9-10ppm, about four times greater than that of uranium. However, having lower activity than uranium, the radioactivity concentration of thorium and uranium is about the same. High concentrations of thorium (~10%) are found in monazite, a rear-earth mineral. Owing to its high level of radioactivity, people living close to monazite sands can be exposed to high doses of radiation.

Measurement of natural radiation has found many applications. Because of the high level of natural radioactivity in shales it is used to distinguish between shales and other sediments. It is widely used in borehole logging for coal to delineate the coal seams due to the fact that coal contains much less radioactive elements than the interseam sediments. The measurement of natural gamma radiation is a very simple and effective technique because does not require the use of an artificial source of radiation. It is recommended to be used as a spectrometric technique e.g. to record the energy spectra recorded at different depths in borehole applications or other applications. The spectrometric natural gamma logs are also useful for lithology identification when combined with other geophysical logs.

4.1 Application: Uranium

Uranium is a good example for the application of natural gamma radiation in nuclear borehole logging and was chosen due to its resurgence as a source of energy. γ-rays emitted from the uranium minerals are routinely used for both quantitative and qualitative determination of uranium in exploration or ore-body evaluation. The γ-rays are ideal to use as intrinsic indicators for uranium as they occur naturally, sample relatively large volumes of material, and are simple to detect and identify. The decay series of ^{238}U (excluding some short lived isotopes) is

$$^{238}U \xrightarrow{4.5\times10^{9}\,y} {}^{234}U \xrightarrow{2.5\times10^{5}\,y} {}^{230}Th \xrightarrow{8\times10^{4}\,y} {}^{226}Ra \xrightarrow{1620\,y} {}^{222}Rn \xrightarrow{3.8\mathrm{d}} \cdots {}^{214}Pb \xrightarrow{27m} {}^{210}Pb \xrightarrow{20\,y} {}^{206}Pb(stable)$$

When secular equilibrium is reached after some 10^6 years, the activity of each isotope, except ^{206}Pb, in the decay series is equal. Disequilibrium can occur throughout the chain if one or more of the daughter products are lost by any process other than radioactive decay. Since each daughter product is an element with its own characteristic physical and chemical properties it may behave differently within a given environment. For example, ^{222}Rn is a gas. Also, the solubilities of radium, uranium and thorium differ, and preferential leaching of elements may occur.

Total γ-ray logging is probably the easiest logging technique for quantitative analysis. The total number of γ-rays can be recorded with either a Geiger counter or a scintillator. The logging probes are calibrated in special uranium test pits. Since this method records γ-rays from many daughters of uranium, it can only be applied for quantitative analysis if both the test pit and uranium ore body are in secular equilibrium.

Accurate spectral γ-ray logging. The principle of this technique for the in situ quantitative determination of uranium (Tanner et al., 1977) is measurement of the γ-radiation (1001 keV) produced during the decay of protactinium-234 (^{234}Pa) to uranium-234. In the uranium decay series, ^{238}U first decays to ^{234}Th, which decays to ^{234}Pa, which in turn decays to ^{234}U. Because the half-lives of all three reactions are short, it is unlikely that in nature the ^{238}U and ^{234}Pa will become separated. Thus, the determination of the ^{234}Pa grade from the count rate of the 1001 keV γ-ray gives a measure of the ^{238}U grade in the ore body. The method is independent of the amount of disequilibrium in the ore body. A high resolution (intrinsic Ge detector) is necessary to measure the count rate of the 1001 keV which is weak in comparisson to other γ-ray lines in the natural γ spectrum.

5. ACTIVE LOGGING

5.1. The backscatter gamma-gamma technique

This technique which is widely used in nuclear borehole logging for density measurements relies on the gamma ray scattering and absorption. The fundamentals of gamma ray scattering/absorption are briefly reviewed below.

Scattering and absorption of gamma radiation: The interaction of gamma radiation with matter in the energy range from 50 keV to 50 MeV is dominated by three processes: i. photoelectric effect, ii. Compton effect and iii. pair production.

In the photoelectric effect, predominant at low energies, the γ-ray (photon), gives all its energy to a bound electron. The electron, to overcome its binding energy in the atom, uses part of the energy and the rest is taken as kinetic energy. The energy of the emitted electron is therefore $E_e = E_\gamma - E_b$, where E_γ is the γ-ray energy and E_b is the binding energy of the electron in the atom, usually the k-shell energy. The probability for a photon to interact with an electron in a given orbit is higher when the energy of the photon is equal to the binding energy and decreases with increasing energy. The electron gives up its energy to other atoms and eventually falls back into an orbit. The X-rays emitted following the capture of the electrons into orbits interact with the matter again and again until all the energy is absorbed either at very low energy orbital levels or other mechanisms.

The cross section of the photoelectric absorption per atom is a function of photon energy, E, and is approximated as being proportional to

$$\sigma(E) \approx \frac{Z^{4.5}}{E^n} \quad 2.5 \le n \le 3.5$$

The contribution of the photoelectric effect at low energies is significant for heavy elements because of their high atomic number. For light elements, the contribution of the photoelectric effect is reduced as a result of the linear relationship between its cross-section and $Z^{4.5}$.

The Compton effect predominates around 1 MeV. It implies scattering of photons by the atomic electrons. The photon is deflected from its trajectory with or without loss of energy. This happens at photon energies much larger than the electron binding energies so that, theoretically, the electrons can be assumed free.

In the pair production effect, a photon disappears with the creation of an electron/positron pair. The total kinetic energy of the resulting particles is equal to the photon energy minus the mass energy of the electron/positron pair created by the interaction (1.02 MeV) and therefore the pair production can not take effect below 1.02 MeV. The pair production takes place in the field of a nucleus or electron with no change of the state of the nucleus or its electrons. The nucleus must be present to absorb some of the momentum of the photon.

There are other interactions like resonance scattering of gamma rays or photonuclear reactions. Gamma ray resonance scattering is an elastic process that takes place via an excited state of a stable nucleus. If the energy of the gamma ray corresponds exactly to the energy level of the stable nucleus, the nucleus can absorb this gamma ray and become an unstable excited nuclear state. The nucleus will regain its stable state by emitting a gamma ray that is theoretically of the same energy as the one absorbed. In practice, the gamma ray emitted by the excited nucleus at rest has less energy than the photon that excited the nucleus because of the recoil energy taken by the nucleus. Mössbauer discovered that an atom embedded in a crystal lattice, can emit or absorb γ-radiation without loss from the recoil because the momentum is taken up by the crystal as a whole with negligible energy loss. The resonance scattering is not used much in nuclear borehole logging. In photonuclear reactions, γ-rays of high energies produce nuclear reactions with atomic nuclei. If the incident γ-ray energy exceeds a threshold energy, it is possible to remove particles from stable nuclei. Each element is characterized by particular threshold energy. The most frequent nuclear reactions induced by high-energy γ-rays in the energy range of interest are (γ,n) processes. The maximum cross-section for light elements is at 20-25 MeV and ≅ 15 MeV with other elements. The photoneutron reaction has found practical applications mostly for the determination of low atomic number elements. The technique is selective if the (γ,n) threshold energies are selected appropriately.

Concept of Equivalent Atomic Number, Z_{eq} It is convenient to introduce the concept of equivalent atomic number, Z_{eq} of the scattering medium. For a mixture of elements with atomic numbers Zi that form the scattering medium, the equivalent atomic number Z_{eq} is defined as

$$Z_{eq} = Z = \sqrt[3.5]{\frac{\sum_i W_i \frac{Z_i^{4.5}}{M_{A_i}}}{\sum_i W_i \frac{Z_i}{M_{A_i}}}} \tag{1}$$

where W_i and Z_i are the weight fraction and atomic number of a particular element constituent, *i*, in the scattering medium. Z_{eq} can be seen as a substitute for Z for a multielement medium.

With the assumption that Z_i/M_{Ai} is a constant for low elements,

$$Z_{eq} = \sqrt[3.5]{\sum_i W_i Z_i^{3.5}} \tag{2}$$

Equation (2) shows the strong dependence of the Z_{eq} of a medium on the constituent element with the highest atomic number. This dependence can be used to determine the concentration of a high – Z element in a matrix of low-Z elements, e.g. the percentage of Fe in iron ore, ash in coal, etc.

5.1.1 Applications to Nuclear Borehole Logging

Practical Methods of Density and Zeq Measurements When there is access to both sides of the medium under investigation, the density and Zeq are determined by measuring the direct attenuation of γ-radiation passing through the medium. When only one side of the medium is available, as it is in a borehole, the detector and the source are placed on the same side of the medium. Shielding is used to stop the gamma rays from the source reaching the detector.

When only one side of the medium is available, e.g. boreholes, the detector and the source are placed on the same side of the medium. Shielding is used between the source and detector so that the detector records only backscattered radiation. Figure 1 shows schematically the geometry used in the gamma-gamma technique together with the γ-ray backscattered energy spectrum recorded by the detector. The γ-rays from the source undergo successive Compton scattering with loss of energy after each scattering. Below 300 keV the photoelectric absorption increases with decreasing γ-ray energy. The theory shows that the high energy of the spectrum, above 300 keV, is a function of the electronic density of the scattering medium, and below 300 keV both photoelectric and Compton effects are present. The theory also shows that the ratios of count rates recorded in two energy windows, at high and low energy, is a function only of the Z_{eq} of the medium. The density is determined from the number of γ-rays above ~300 keV recorded in the backscattered spectrum.

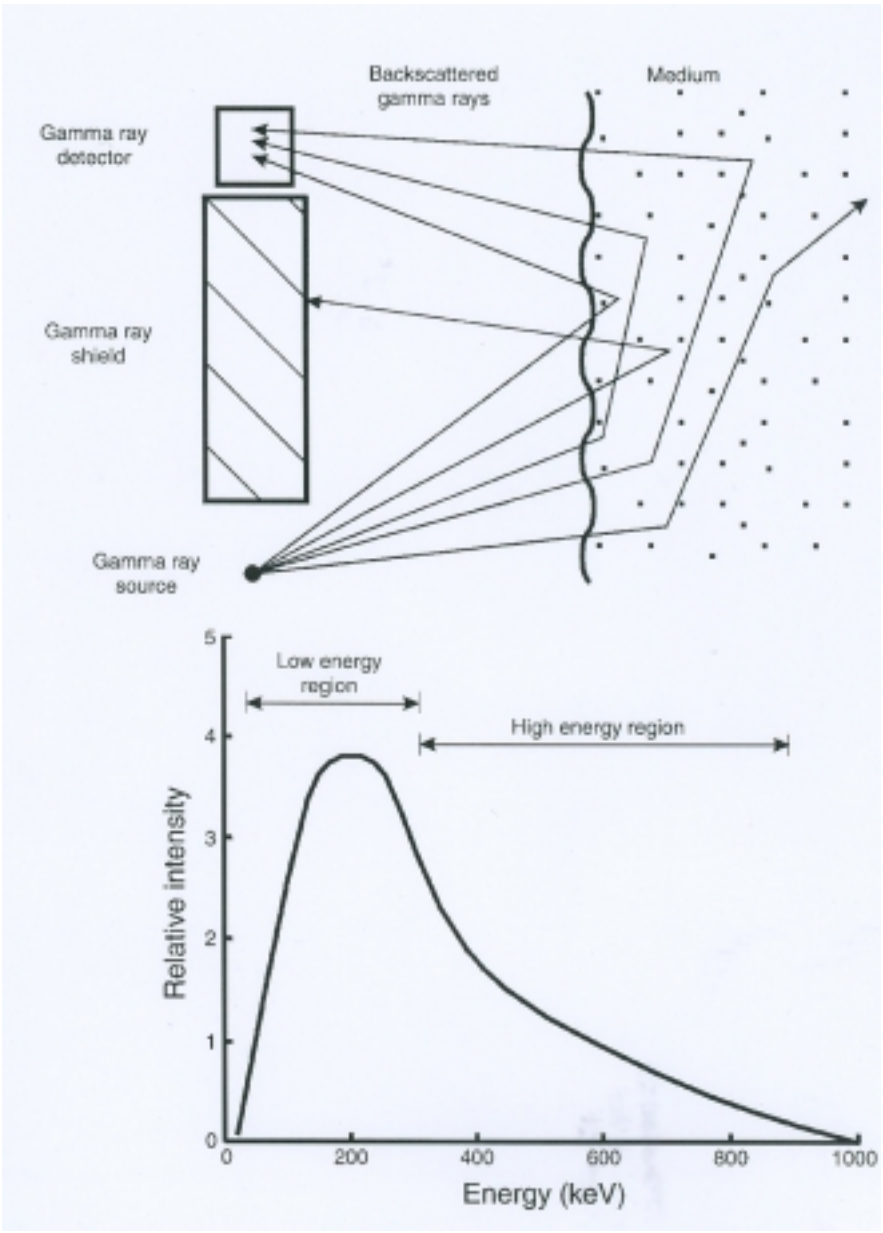

Figure 1 Schematic representation of the backscattered gamma rays and a backscattered gamma ray spectrum.

This can be achieved either in a spectrometric or nonspectrometric measurement.

In a nonspectrometric measurement the γ-rays below ~300 keV are stopped from reaching the detector by an absorber. Zeq is determined only in the spectrometric technique where it is possible to measure the γ-ray count rates in different windows set in the energy spectrum.

The Delineation of Coal Seams Intersected by Boreholes and Determination of Ash in Coal Seams. Ash content in coal is the weight percentage of residue after combustion; it is closely related to the mineral content of coal. The most common technique for the determination of ash in coal seams is the nonspectrometric gamma-gamma technique. This technique was developed for the coal industry during 1970s (2-6). The bed resolution (BRD), high resolution (HRD) and long-spaced (LSD) density logs are used to delineate the coal seams and measure the density. The density of the coal seams intersected by the boreholes is determined by the gamma-gamma logging and the ash contend of coal is determined from the correlation that exists between density and ash content in coal seams. To achieve high accuracy for the determination of ash, it is essential that a high correlation exists between density and ash content. While many coal deposits exist where this correlation is high, in other coal deposits there are significant fluctuations in the relationship between ash content and density (7). When the correlation between ash content and density is not high, the spectrometric gamma-gamma technique provides an alternative method for the determination of ash in coal seams (8). The technique is based on the correlation between Z_{eq} and ash content. This is the case if the chemical composition of ash is stable. However, an important source of error in the measurement of ash content of coal arises if the concentration of ash components of high Z atomic number, such as Fe, Ti, Ca, etc., shows considerable variation in the ash. As mentioned above, Z_{eq} is determined from the ratio of the count rates recorded in two energy windows set at high and low energies. The nonspectrometric gamma-gamma tools are normally excentralised and employ ^{137}Cs or ^{60}Co gamma ray sources of activity above 2 GBq.

The spectrometric tool is centralised and employs a much weaker source of 60 MBq.

In Situ Analysis Using Ultra-Low Radiation Intensity Gamma Ray Sources In response to the demand for techniques employing very low activity gamma-ray sources (below 3.7 MBq activity), a new tool employing the backscattered gamma-gamma technique was developed (8). The tool has a very short source to detector distance (30 mm) and is using a ^{137}Cs source of very low activity (1.8 MBq). The tool was developed for the delineation of coal seams intersected by boreholes and in situ determination of the coal ash in the coal seams. The same tool was applied successfully to delineate the iron ore deposit and to predict its grade (9) and for orebody delineation and grade control of zinc-lead ore (10, 11). A related technique was later applied to develop and manufacture a stockpile probe for the determination of the ash in coal stockpiles (12). The backscattered gamma-gamma technique employing a very low activity gamma-ray source was also applied in a 2π geometry in the coal face ash analyser to measure the ash content on the coal face (13, 14). The coal face analyser was later developed for the determination of %Pb on Pb-Zn ore surface (15).

The gamma-gamma technique can delineate the coal seams or some metalliferous ore bodies and determine the density (along the borehole). It has got limited application for grade control (e.g. ash, Fe, Pb). It is not a useful technique for the determination of the elemental composition in a particular matrix. A different technique, prompt gamma neutron activation analysis (PGNAA) is applied for in situ determination of elemental composition in boreholes.

5.2 Prompt Gamma Neutron Activation Analysis

This technique is based on the neutron capture reaction and employs a neutron source as the primary source of radiation. In order to understand this technique a background knowledge on the interaction of neutrons with nuclei is needed.

Interaction of Neutrons With Matter The neutron energies are arbitrarily classified as: fast neutrons (above 500 keV), intermediate (1 keV to 500 keV) and slow (below 1 keV). Slow neutrons are further subdivided as epithermal neutrons (from 0.1 eV to 1 keV) and thermal neutrons (below 0.1 eV). A fast neutron suffers many interactions in the process of losing its energy to reach thermal energy. This process is called slowing down. The neutron may disappear during this process as a result of nuclear reactions when the neutron impinges on nuclei forming the scattering medium. There are four types of interactions that can occur between the neutron and the surrounding nuclei:

(i) Particle reactions (n,x), e.g. (n,α), (n,p), (n,xn) (for neutrons of high energy only). This reaction involves the release of a charged particle or more than one neutron. The final product cannot be the same as the target nucleus. Characteristic γ-rays are emitted and the reaction can be used to identify the presence of particular elements in materials or for the determination of their concentration.

(ii) Inelastic scattering (n,n'γ) when the neutron interacts with a nucleus of atomic number Z and mass number A to form a compound nucleus in an excited state of mass A + 1. The compound nucleus decays very rapidly to the ground state by emitting a γ-ray, and it then emits a neutron. The γ-rays that are produced are characteristic of the energy levels of the compound nucleus and can be used to identify the target nucleus.

The neutron energy must be above a threshold characteristic for each element (normally above 1 MeV).

(iii) Elastic scattering is the most important interaction for neutrons produced by isotopic sources (average energy below 4.5 MeV). Although the neutron reaction and inelastic scattering reduce the neutron population, their importance is modest by comparison with the neutron scattering. Most of the neutrons reach low energies through repeated elastic collisions. A percentage of the incident neutron's kinetic energy is transferred to the recoiling nucleus and the neutron will have less kinetic energy after collision. Hydrogen has a unique position in slowing down neutrons by elastic scattering. The average number of scatterings calculated for a few elements commonly found in the earth' crust to slow down a neutron of 14 MeV, produced by a neutron generator, to thermal energy (0.01 eV) are: H(19), C(112), O(154), Al(290), Si(297), Fe(539). Hydrogen's position is further enhanced when taken into account scattering cross-sections. The proton's scattering cross-section between $\approx 10^5$ eV and 0.5 eV is about 20 barn by comparison to several barn for the other nuclei mentioned above.

(iv) Radiative (neutron) capture: once slowed down to thermal energies, neutrons diffuse through the medium without further loss of energy until their life is terminated by other processes such as radiative capture. In this process, the thermal neutron enters the nucleus, producing a compound nucleus in an excited state, which then decays to the ground state by the emission of one or more γ-rays that are characteristic of the capture nucleus. The radiation capture process only takes 10-11 s, which is virtually instantaneous compared with the initial slowing down and diffusion process, which may take several hundred microseconds. The product nucleus may be stable or it may decay (with a half-life of between a few microseconds and a number of years) to another product nucleus, often with β-particle emission. This is called thermal neutron activation.

Application of PGNAA in nuclear borehole logging Neutron-capture and inelastic scattering are the most common interactions used in borehole logging. The capture γ-rays produced by the main constituents of the earth crust Al, Si, Fe, Ca, Cl and S have energies above 3 MeV as shown in table 1. However, the γ-rays produced by neutron activation, neutron inelastic scattering, or natural radioactivity have energies mainly below 3 MeV. This makes the prompt neutron gamma method less sensitive to interferences from other neutron interactions. The deeply-penetrating high energy γ-rays emanate from a large volume of coal and this makes the neutron capture technique less sensitive to the rugosity and condition of the borehole than the gamma-gamma technique. The neutron gamma technique also samples a larger volume of medium investigated than does the gamma-gamma method.

5.2.1 Applications to Nuclear Borehole Logging

The neutron source most commonly used in PGNAA logging is ^{252}Cf. The mean neutron energy spectrum of ^{252}Cf is appreciably lower than that of Am-Be. This makes ^{252}Cf a better candidate for PGNAA, a technique based on thermal neutrons. Also, ^{252}Cf is more environmentally acceptable for routine borehole logging applications because of its shorter half-life (2.64 yr). For these reasons, it was used for this work. The BGO detector is best suited for neutron capture measurements due to its higher efficiency for high energy γ-rays than either NaI(Tl) or CsI(Na). BGO is also less sensitive to neutron activation and capture than the other two scintillators. This detector was used in the applications mentioned below.

Coal. Owing to its high hydrogen content, coal is an excellent medium for the neutron capture technique. The neutrons emitted by the neutron source are thermalised by colliding with the hydrogen nuclei present in coal and subsequently interact with the nuclei in the coal matrix. The basis for ash determination is the correlation that exists between ash and the main constituents of ash, i.e. Al, Si and Fe. The PGNAA technique for the determination of ash content, depth and thickness of coal strata in waterfilled boreholes was developed during 1980s (16). The technique was later extended to dry boreholes (17). Further developments proved that this technique is capable for the in-situ determination of ash, Fe, Si, Al, S and density of coal seams (18 – 20). The technique is also able to determine in situ the deformation temperature of coals for which a correlation exists between the deformation temperature and the percentage of Al, Si and Fe present in coal.

Table 1. Neutron capture data for major components in the earth crust.

Element (atomic mass)	*Cross-section σ(barn)**	*Major γ-rays (MeV)*	*γ-ray intensity (I) per 100 neutron radiative captures*
Chlorine (35.45)	33	5.7	5.5
		6.1	20
		6.62	8.0
		6.63	4.5
		7.4	10.4
		7.79	8.5
Aluminium (26.98)	0.23	7.72	27.4
		7.69	4.2
		6.10	2.3
		5.13	2.6
		4.91	2.6
		4.69	3.9
		4.66	2.1
		4.13	6.4
Iron (55.85)	2.55	7.65	28.5
		7.63	24.1
		6.02	9
		5.92	9
Silicon (28.09)	0.16	7.2	7.8
		6.38	12.4
		4.93	62.7
		3.66	3.9
		3.54	68.0
		2.09	21.5
		1.16	19.9
Sulphur (32.06)	0.52	0.84	75.5
		2.38	44.5
		2.93	22.3
		3.22	27.1
		5.40	59.1
Calcium (40.08)	0.43	1.94	72.5
		4.42	14.9
		6.42	38.9

*Thermal neutron capture

Iron ore. Nuclear logging was tested for the in situ determination of Fe, Si and Al in iron ore blastholes (21). PGNAA was used to determine percentage of Fe and Si while natural gamma logging was employed for the determination of Al. The accuracy given by nuclear logging is comparable to the accuracy provided by the laboratory analysis which was determined by taking the average of four samples collected from the cuttings deposited on the surface around the perimeter of a drill hole.

Acid mine drainage. Acid Mine Drainage is produced by the oxidation of sulphidic mine wastes that are exposed to atmospheric conditions and is one of the biggest environmental issues facing most sectors of the mining industry including coal, precious metals, base metals and uranium. PGNAA can measure total sulphur in overburden rock. Total sulphur is an important parameter in the estimation of the net acid producing potential (NAPP) of the rock and its estimation has a substantial contribution for developing an acid rock drainage control management plan. An interesting result from our work was the establishment of a correlation between net acid drainage (NAG) and the PGNAA log (22). This is important especially when NAG and total sulphur in the rock are not correlated, as was the case where the work was carried out.

Other applications. PGNAA logging technique proved valuable for other applications, e.g. salinity, copper, nickel, zinc and other types of mineralizations. However, the purpose of this paper was only to point to some of the applications of nuclear physics to geophysics. This is an example of how knowledge acquired from fundamental physics finds its way to increase the productivity in industry and raise the standard of living of the population.

6. CONCLUSIONS

Nuclear techniques are more widely used in the oil industry than in the mineral industry. They provide vital information for the oil industry which can not be obtained by any other means. However, new applications were developed for the mining industries in the last 10 years and more applications are expected when new type of detectors becomes available. Nuclear geophysics is a mature field of research and incremental development rather than spectacular is expected in the future.

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